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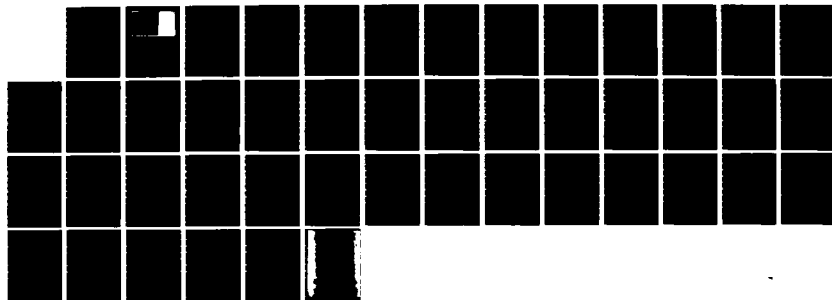
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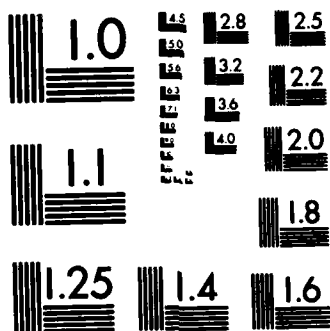
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WITH UNBOUNDED CONTROL ACTION

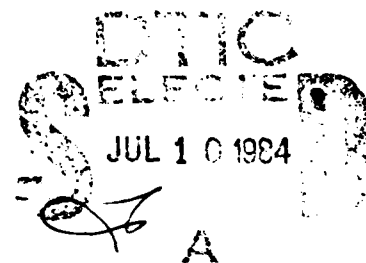
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SYSTEMS WITH UNBOUNDED CONTROL ACTION

R.F. Curtain* and D. Salamon**

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ABSTRACT

This paper contains a design procedure for constructing finite dimensional compensators for a class of infinite dimensional systems with unbounded input operators. Applications to retarded functional differential systems with delays in the input or the output variable and to partial differential equations with boundary input operators are discussed.



AMS (MOS) Subject Classifications: 34K20, 93C15, 93C25, 93D15

Key Words: Infinite Dimensional Systems, Unbounded Input Operators, Compensator, Retarded Functional Differential Equations, Partial Differential Equations, Boundary Control

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SIGNIFICANCE AND EXPLANATION

For a large number of control and observation processes appropriate mathematical models incorporate partial or functional differential equations and therefore give rise to differential equations in an infinite dimensional state space. In order to improve the stability properties of the underlying process, dynamic compensators have to be designed. A straight forward generalization of the finite dimensional theory leads to compensators which themselves are infinite dimensional systems and therefore cannot be implemented directly. Hence the question arises whether it is possible to stabilize an infinite dimensional system through a finite dimensional compensator. This problem is not new, however previous results are restricted either to a special class of infinite dimensional systems or to systems with bounded input/output-operators. But for many control and observation processes there are severe limitations such as delays in the control actuator and measurement devices and restrictions of controls and sensors to a few points of the boundary of the spatial domain. Modelling such limitations results in unbounded input/output-operators.

It is the purpose of this paper to present a general approach for the design of finite dimensional compensators for infinite dimensional systems which allows for unbounded input/output-operators and can be applied to parabolic and hyperbolic PDEs as well as retarded and neutral FDEs.

The responsibility for the wording and views expressed in this descriptive summary lies with MRC, and not with the authors of this report.

FINITE DIMENSIONAL COMPENSATORS FOR INFINITE DIMENSIONAL
SYSTEMS WITH UNBOUNDED CONTROL ACTION

R.F. Curtain* and D. Salamon**

1. INTRODUCTION

In [15], [16], [17] SCHUMACHER presented a design procedure for constructing stabilizing compensators for a class of infinite dimensional systems. The novel feature was that the compensators were finite dimensional and that they could be readily numerically calculated from finitely many system parameters. The class included those systems described by retarded functional differential and partial differential equations provided that the eigenvectors of the system operators were complete and provided that the input and output operators were bounded. In [3] CURTAIN presented an alternative compensator design which applied to essentially the same class of systems, except that for the special case of parabolic systems unbounded input and output operators were allowed. By means of enlarging the state space of the given distributed boundary control system, CURTAIN in [2] essentially transformed the original problem with unbounded control into one with bounded control action so that the techniques of either [16] or [3] could be applied. The resulting control, however, was of integral type. Neither of these two compensator designs are applicable to retarded systems with delays in the control or the observation.

In the present paper we make use of the abstract approach developed by SALAMON [14] to extend the results of SCHUMACHER [16] to allow for unbounded control action. This is done in a direct way without reformulating the original problem into one with a bounded input operator. In section 2 we outline the abstract formulation and prove a theorem on the existence of a finite dimensional compensator paralleling the development in [16]. In section 3 the general approach is then applied to retarded functional differential systems

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with delays in either the input or the output variables. The conditions are easy to check and they are quite reasonable, except for the assumption of completeness of the eigenfunctions which seems to be too strong. In a special case we are able to weaken this assumption.

Finally, in section 4, we show how boundary control systems fit into the abstract framework of section 2 and give an example. The results are compared with the approach in [3].

2. A GENERAL RESULT

We consider the abstract Cauchy problem

$$\begin{aligned} (2.1;1) \quad & \dot{x}(t) = Ax(t) + Bu(t), \quad x(0) = x_0 \in X, \\ (2.1;2) \quad & y(t) = Cx(t), \end{aligned}$$

on the real, reflexive Banach space X where $A : D(A) \rightarrow X$ is the infinitesimal generator of a strongly continuous semigroup $S(t)$ on X and $C \in L(X, \mathbb{R}^n)$.

In order to give a precise definition of what we mean by an unbounded input operator we need an extended state space $Z \supset X$. For this purpose let us first introduce the subspace

$$Z^* = \mathcal{D}_X(A^*) \subset X^*$$

endowed with the graph norm of A^* . Then Z^* becomes a real, reflexive Banach space and the injection of Z^* into X^* is continuous and dense. Defining Z to be the dual space of Z^* , we obtain by duality that

$$X \subset Z$$

with a continuous dense injection.

REMARKS 2.1

- (i) A^* can be regarded as a bounded operator from Z^* into X^* and $S^*(t)$ restricts to a strongly continuous semigroup on Z^* . By duality, A extends to a bounded operator from X into Z . This extension, regarded as an unbounded operator on Z , is the infinitesimal generator of the extended semigroup $S(t) \in L(Z)$ (see [14, Lemma 1.3.2]).
- (ii) If $\mu \notin \sigma(A) = \sigma(A^*)$, then the operator $\mu I - A : X \rightarrow Z$ is bijective. Furthermore, this operator commutes with the semigroup $S(t)$ so that it provides a similarity action between the semigroups $S(t) \in L(X)$ and $S(t) \in L(Z)$.
- (iii) It follows from (ii) that the exponential growth rate of the semigroup $S(t)$ is the same on the state spaces X and Z , i.e.

$$\omega_0 = \lim_{t \rightarrow \infty} t^{-1} \log \|S(t)\|_{L(X)} = \lim_{t \rightarrow \infty} t^{-1} \log \|S(t)\|_{L(Z)}.$$

- (iv) It also follows from (ii) that the spectrum of A on the state space X coincides with the spectrum of A on Z (see [14, Lemma 1.3.2]). Furthermore, the generalized eigenvectors for both operators are the same, since the eigenvectors of A on Z are contained in $\mathcal{D}_Z(A) = X$. Finally, the (generalized) eigenvectors of A are complete in X if and only if they are complete in Z .

We will always assume that B is a bounded, linear operator from \mathbb{R}^l into Z . However, we want the solutions of (2.1;1) to be in the smaller space X on which the output operator is defined. Therefore we need the following hypothesis.

- (H1) For every $T > 0$ there exists a constant $b_T > 0$ such that $\int_0^T S(T-s)Bu(s)ds \in X$ and

$$\left\| \int_0^T S(T-s)Bu(s)ds \right\|_X < b_T \|u(\cdot)\|_{L^p[0,T;\mathbb{R}^l]}$$

for every $u(\cdot) \in L^p[0,T;\mathbb{R}^l]$ where $1 < p < \infty$.

In the following we collect some important consequences of (H1) which have been established in [14, section 1.3].

REMARKS 2.2

(i) (H1) is satisfied if and only if the inequality

$$\|B^* S^*(\cdot) x^*\|_{L^q[0,T;R^l]} < b_T \|x^*\|_{X^*}$$

holds for every $x^* \in Z^*$ and every $T > 0$ where $1/p + 1/q = 1$.

(ii) If (H1) is satisfied, then

$$(2.2) \quad x(t) = S(t)x_0 + \int_0^t S(t-s)Bu(s)ds \in X$$

is the unique strong solution of (2.1;1) for every $x_0 \in X$ and every

$u(\cdot) \in L^p[0,T;R^l]$. More precisely $x(t)$ is continuous in X on the interval $[0,T]$ and satisfies

$$x(t) = x_0 + \int_0^t [Ax(s) + Bu(s)]ds, \quad 0 < t < T,$$

where the integral has to be understood in the state space Z . Thus equation (2.1;1) is satisfied in the space Z for almost every $t \in [0,T]$.

(iii) If (H1) is satisfied, then for every $w(\cdot) \in C[0,T;X]$ there exists a unique $x(\cdot) \in C[0,T;X]$ satisfying the equation

$$x(t) = w(t) + \int_0^t S(t-s)BFx(s)ds, \quad t > 0.$$

This solution $x(\cdot)$ depends continuously on $w(\cdot)$.

Moreover hypothesis (H1) implies the following important perturbation result.

THEOREM 2.3

Let $F \in L(X; \mathbb{R}^k)$ be given. Then the following statements hold.

(i) There exists a unique strongly continuous semigroup $S_F(t)$ on X satisfying

$$(2.3) \quad S_F(t)x = S(t)x + \int_0^t S(t-s)BFS_F(s)x ds$$

for every $x \in X$ and every $t > 0$. Its infinitesimal generator is given by

$$D(A_F) = \{x \in X | Ax + BFx \in X\},$$

$$A_F x = Ax + BFx.$$

(ii) $A_F^* = A^* + F^* B^* : D(A_F^*) = Z^* \rightarrow X^*$.

(iii) $S_F(t)$ extends to a strongly continuous semigroup on Z and the infinitesimal generator of the extended semigroup is given by $A + BF : X \rightarrow Z$.

(iv) Let $x_0 \in X$ and $v(\cdot) \in L^p[0, T; \mathbb{R}^k]$ be given and let $x(\cdot) \in C[0, T; X]$ be the unique solution of

$$(2.4) \quad x(t) = S(t)x_0 + \int_0^t S(t-s)B[Fx(s) + v(s)]ds, \quad 0 < t < T.$$

Then

$$(2.5) \quad x(t) = S_F(t)x_0 + \int_0^t S_F(t-s)Bv(s)ds, \quad 0 < t < T.$$

(v) Hypothesis (H1) is satisfied with $S(t)$ replaced by $S_F(t)$ and $S_F(t)$ satisfies

$$(2.6) \quad S_F(t)x = S(t)x + \int_0^t S_F(t-s)BFS(s)x ds$$

for every $x \in X$ and every $t > 0$.

(vi) Let $x_0 \in X$ and $f(\cdot) \in L^P[0, T; X]$ be given and define

$$(2.7) \quad x(t) = S_F(t)x_0 + \int_0^t S_F(t-s)f(s)ds, \quad 0 \leq t \leq T.$$

Then

$$(2.8) \quad x(t) = S(t)x_0 + \int_0^t S(t-s)[BFx(s) + f(s)]ds, \quad 0 \leq t \leq T.$$

PROOF Statement (i) has been shown in [14, theorem 1.3.7] and (ii) follows from [14, theorem 1.3.9] since the input space is finite dimensional. By (ii), $S_F^*(t)$ restricts to a strongly continuous semigroup on $Z^* = \mathcal{D}(A_F^*)$ and hence $S_F(t)$ extends to a semigroup on Z . By remark 2.1(i), the extended semigroup is generated by the adjoint operator of A_F^* , where A_F^* is regarded as a bounded operator from Z^* into X^* . This proves statement (iii).

In order to establish statement (iv), let us first assume that $v(\cdot) \in C^1[0, T; \mathbb{R}^l]$ and let $x(\cdot) \in C[0, T; X]$ be the unique solution of (2.4). Then it follows from Remark 2.2 (ii) that $x(\cdot) \in C^1[0, T; Z]$ and

$$d/dt \, x(t) = (A + BF)x(t) + Bv(t), \quad 0 \leq t \leq T.$$

Hence it follows from (iii) and a classical result in semigroup theory that $x(\cdot)$ is given by (2.5). In general, statement (iv) follows from the fact that the unique solutions of both (2.4) and (2.5), regarded as continuous functions with values in Z , depend continuously on $v(\cdot) \in L^P[0, T; \mathbb{R}^l]$.

It follows immediately from (iv) that (H1) is satisfied with $S(t)$ replaced by $S_F(t)$. Now let $x(t)$, $t > 0$, be defined by the RHS of (2.6). Then it follows from (iv) that

$$\begin{aligned}
x(t) &= S(t)x + \int_0^t S(t-s)B \left[F \int_0^s S_F(s-\tau)BFS(\tau)x d\tau + FS(s)x \right] ds \\
&= S(t)x + \int_0^t S(t-s)BFx(s)ds
\end{aligned}$$

for $t > 0$, and hence $x(t) = S_F(t)x$, by the definition of $S_F(t)$. This proves statement (v).

Statement (vi) can be established straight forwardly by inserting (2.3) into (2.7) and interchanging integrals.

The aim of this section is to give sufficient conditions under which system (2.1) can be stabilized by a finite dimensional compensator of the form

$$(2.9;1) \quad \dot{w}(t) = Mw(t) - Hy(t), \quad w(0) = w_0,$$

$$(2.9;2) \quad u(t) = Kw(t) + v(t),$$

where $M \in \mathbb{R}^{N \times N}$, $H \in \mathbb{R}^{N \times m}$, $K \in \mathbb{R}^{l \times N}$ are suitably chosen matrices. To this end we need the following well posedness result for the connected system (2.1), (2.9).

PROPOSITION 2.4

Let (H1) be satisfied. Then for all $x_0 \in X$, $w_0 \in \mathbb{R}^N$, $v(\cdot) \in L_{loc}^p[0, \infty; \mathbb{R}^l]$ there exists a unique solution pair $x(t), w(t)$ of (2.1) and (2.9). This means that $x(t)$ is continuous in X and absolutely continuous in Z , that (2.1;1) is satisfied for almost every $t > 0$ where $u(t)$ is given by (2.9;2) and that $w(t) \in \mathbb{R}^N$ is continuously differentiable and satisfies (2.9;1) where $y(t)$ is given by (2.1;2).

PROOF Let us introduce the spaces $X_0 = X \times \mathbb{R}^N$, $Z_0 = Z \times \mathbb{R}^N$, $U_0 = \mathbb{R}^l \times \mathbb{R}^m$ and the operators $S_0(t) \in L(X_0)$, $B_0 \in L(U_0, Z_0)$, $F_0 \in L(X_0, U_0)$ by

$$S_e(t) = \begin{bmatrix} S(t) & 0 \\ 0 & e^{Mt} \end{bmatrix}, B_e = \begin{bmatrix} B & 0 \\ 0 & -H \end{bmatrix}, F_e = \begin{bmatrix} 0 & K \\ C & 0 \end{bmatrix}.$$

Then hypothesis (H1) is satisfied with $X, Z, S(t), B$ replaced by $X_e, Z_e, S_e(t), B_e$, respectively. Moreover $x(t) \in X$ and $w(t) \in \mathbb{R}^N$ satisfy (2.1) and (2.9) in the above sense if and only if the following equation holds for every $t > 0$

$$\begin{pmatrix} x(t) \\ w(t) \end{pmatrix} = S_e(t) \begin{pmatrix} x_0 \\ w_0 \end{pmatrix} + \int_0^t S_e(t-s) B_e \left[F_e \begin{pmatrix} x(s) \\ w(s) \end{pmatrix} + \begin{pmatrix} v(s) \\ 0 \end{pmatrix} \right] ds.$$

This proves the statement of the Proposition.

The following hypothesis together with (H1) will turn out to be sufficient for the existence of a stabilizing, finite dimensional compensator for system (2.1). It generalizes the approach of SCHUMACHER [15], [16], [17] to systems with unbounded input operators.

- (H2) Suppose that there exist operators $F \in L(X, \mathbb{R}^l)$, $G \in L(\mathbb{R}^m, X)$ and a finite dimensional subspace $W \subset X$ such that the following conditions are satisfied.
1. The feedback semigroup $S_F(t) \in L(X)$, defined by (2.3), is exponentially stable.
 2. The observer semigroup $S^G(t) \in L(X)$, generated by $A + GC$ is exponentially stable.
 3. $S_F(t)W \subset W$ for all $t > 0$.
 4. $\text{Range } G \subset W$.

If (H2) is satisfied and $N = \dim W$, then there exist linear maps $\iota : \mathbb{R}^N \rightarrow X$, $\pi : X \rightarrow \mathbb{R}^N$ satisfying

$$(2.10) \quad \pi \iota = \text{id}, \iota \pi x = x, \quad x \in W.$$

Moreover, $w \in D(A_F)$ and hence πA_F is a well defined linear map on R^N . We will show that the system

$$(2.11) \quad \begin{aligned} \dot{w}(t) &= \pi(A_F + GC)w(t) - \pi Gy(t), \quad w(0) = w_0, \\ u(t) &= Fw(t), \end{aligned}$$

defines a stabilizing compensator for the Cauchy problem (2.1).

THEOREM 2.5

If (H1), (H2) and (2.10) are satisfied, then the closed loop system (2.1), (2.11) is exponentially stable.

PROOF By Proposition 2.4, the system (2.1), (2.11) is a well posed Cauchy problem. Now let $x(t) \in X$, $w(t) \in R^N$ be any solution pair of (2.1), (2.11) and define

$$(2.12) \quad z(t) = w(t) - x(t) \in X, \quad t \geq 0.$$

Then

$$(2.13) \quad \dot{w}(t) = \pi A_F w(t) + \pi GCz(t),$$

and hence, using $\pi S_F(t) = e^{\pi A_F t}$ and Theorem 2.3 (vi) with $f(t) = GCz(t)$, we get

$$\begin{aligned} z(t) &= \pi S_F(t)w_0 + \int_0^t \pi S_F(t-s)\pi GCz(s)ds - x(t) \\ &= S_F(t)w_0 + \int_0^t S_F(t-s)GCz(s)ds - x(t) \\ &= S(t)w_0 + \int_0^t S(t-s)[BFw(s) + GCz(s)]ds \end{aligned}$$

$$\begin{aligned}
&= S(t)x_0 - \int_0^t S(t-s)Bu(s)ds \\
&= S(t)z(0) + \int_0^t S(t-s)GCz(s)ds, \quad t > 0.
\end{aligned}$$

This implies $z(t) = S^G(t)z(0)$ and hence, by (2.13), stability of the pair $z(t), w(t)$.
Now the stability of the pair $x(t), w(t)$ follows from (2.12). ■

Clearly, the hypothesis (H2) is not very useful in the present form since it is rather difficult to check in concrete examples. Following the ideas of SCHUMACHER [16], we transform (H2) into an easily verifiable criterion. The basic idea is to approximate G by generalized eigenvectors of A_F and to show that, if A has a complete set of generalized eigenvectors and is stabilizable through B , then there exists a stabilizing feedback operator F which does not destroy the completeness property of A .

More precisely, we need the following assumptions on A .

(H3) The resolvent operator of A is compact and the set $\Lambda = \{\lambda \in \rho(A) \mid \operatorname{Re} \lambda > -\omega\}$ is finite for some $\omega > 0$.

If (H3) is satisfied, then we may introduce the projection operator

$$P_\Lambda = \frac{1}{2\pi i} \int_\Gamma (\mu I - A)^{-1} d\mu$$

where Γ is a simple rectifiable curve surrounding Λ but no other eigenvalue of A . Clearly, P_Λ is a projection operator on both X and Z . Correspondingly we obtain the decomposition

$$X = X_\Lambda \oplus X^\Lambda, \quad Z = Z_\Lambda \oplus Z^\Lambda,$$

where $X_\Lambda = \text{range } P_\Lambda$, $Z^\Lambda = \ker P_\Lambda$, $X^\Lambda = Z^\Lambda \cap X$ are invariant subspaces under $S(t)$. If $N_\Lambda = \dim X_\Lambda$, we may identify X_Λ with \mathbb{R}^{N_Λ} and obtain two maps

$$i_\Lambda : \mathbb{R}^{N_\Lambda} \rightarrow X_\Lambda, \pi_\Lambda : Z \rightarrow \mathbb{R}^{N_\Lambda}$$

with the properties

$$(2.14) \quad \pi_\Lambda i_\Lambda = \text{id}, i_\Lambda \pi_\Lambda = P_\Lambda.$$

Then the projection $x_\Lambda(t) = \pi_\Lambda x(t)$ of a solution to (2.1) satisfies the finite dimensional ODE

$$(2.15) \quad \begin{aligned} \dot{x}_\Lambda(t) &= A_\Lambda x_\Lambda(t) + B_\Lambda u(t), x_\Lambda(0) = \pi_\Lambda x_0 \\ y_\Lambda(t) &= C_\Lambda x_\Lambda(t) \end{aligned}$$

where

$$(2.16) \quad A_\Lambda = \pi_\Lambda A i_\Lambda, B_\Lambda = \pi_\Lambda B, C_\Lambda = C i_\Lambda.$$

Now we can replace (H2) by the following stronger conditions which can in many cases be easily verified. The result has been proved by SCHUMACHER [16] for the case that $\text{range } B \subset X$ (bounded input operator).

PROPOSITION 2.6

Let the operator A satisfy (H3), assume that the exponential estimate

$$(2.17) \quad \|S(t)\|_{X^\Lambda \rightarrow L(X^\Lambda)} < M e^{-\omega t}, \quad t > 0,$$

holds for some $M > 1$ and that the reduced finite dimensional system (2.15) is controllable and observable. Furthermore, assume that the generalized eigenvectors of A are complete in X . Then (H2) is satisfied.

PROOF Since (2.15) is controllable, there exists a matrix $F_A \in \mathbb{R}^{l \times N_A}$ such that the matrix $A_A + B_A F_A$ is stable. Furthermore, the estimate (2.17) implies that

$$\|S(t)\|_{Z_A \rightarrow L(Z_A)} < M e^{-\omega t}, \quad t > 0,$$

(Remark 2.1(iii)). It is a well known result in infinite dimensional systems theory (see e.g. [5] or [16]) that under these assumptions the closed loop semigroup $S_F(t) \in L(Z)$, generated by $A + BF : X \rightarrow Z$ with $F = F_A \pi_A : Z \rightarrow \mathbb{R}^l$ is exponentially stable. By theorem 2.3, $S_F(t)$ restricts to a strongly continuous semigroup on X and the operator $\mu I - A - BF : X \rightarrow Z$ provides a similarity action between both semigroups (Remark 2.1(ii)). Hence the restricted semigroup $S_F(t) \in L(X)$ is still exponentially stable (Remark 2.1(iii)).

By assumption, the generalized eigenvectors of A are complete in X and hence they are complete in Z (Remark 2.1(iv)). Since F is of finite rank, this implies that the generalized eigenvectors of $A + BF : X \rightarrow Z$ are complete in Z (SCHUMACHER [16]). It follows again from the above similarity argument, that this completeness property carries over to the restricted operator $A_F : \mathcal{D}(A_F) \rightarrow X$ introduced in Theorem 2.3 (i).

Now choose $G_A \in \mathbb{R}^{N_A \times m}$ such that $A_A + G_A C_A$ is stable and define $G = \pi_A G_A : \mathbb{R}^m \rightarrow X$. Then it is again a well known fact from infinite dimensional linear systems theory that $A + GC : \mathcal{D}(A) \rightarrow X$ generates an exponentially stable semigroup on X (see [5] or [16]). It is also well known that $A + \hat{GC}$ still generates an exponentially stable semigroup on X whenever $\|G - \hat{G}\|_{L(\mathbb{R}^m, X)}$ is sufficiently small. Now we make use of the fact that the generalized eigenvectors of A_F are complete in X . This implies that $G : \mathbb{R}^m \rightarrow X$ can be approximated arbitrarily close by an operator $\hat{G} : \mathbb{R}^m \rightarrow X$ whose

range is spanned by finitely many generalized eigenvectors of A_P . We choose \hat{G} in such a way that $A + \hat{G}C$ generates a stable semigroup and denote by W the finite dimensional subspace of X which is invariant under A_P and generated by those generalized eigenvectors which span the range of \hat{G} . Since W is a finite dimensional subspace contained in $\mathcal{D}(A_P)$ and invariant under A_P , the restriction of A_P to W is a bounded, linear operator generating a semigroup $S_W(t)$ on W . Since $d/dt S_W(t)x = A_P S_W(t)x$, the semigroup $S_W(t)$ coincides with $S_P(t)$ on W . Hence W is also invariant under the semigroup $S_P(t)$. We conclude that the operators $F : Z \rightarrow R^l$ and $\hat{G} : R^m \rightarrow X$ satisfy hypothesis (H2). \square

Combining Proposition 2.6 with Theorem 2.5, we obtain a constructive procedure for designing a finite dimensional compensator for the Cauchy problem (2.1). The construction is based on the knowledge of the finite dimensional reduced system (2.15) and on the knowledge of sufficiently many eigenvalues and eigenvectors of the operator A_P . For the case of bounded input operators (range $B \subset X$) the procedure has been described in detail by SCHUMACHER [16]. Precisely the same algorithm applies to the case where range $B \not\subset X$.

3. RETARDED SYSTEMS

In this section we apply the abstract result of the previous section to retarded functional differential equations (RFDE) with delays either in the input or in the output variable. If delays occur in the input and output variables at the same time, the RFDE can still be reformulated as an abstract Cauchy problem (see e.g. PRITCHARD-SALAMON [12]) however, the completeness assumption will no longer be satisfied.

3.1 RETARDED SYSTEMS WITH OUTPUT DELAYS

We consider the linear RFDE

$$(3.1) \quad \begin{aligned} \dot{x}(t) &= Lx_t + B_0 u(t) \\ y(t) &= Cx_t \end{aligned}$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^l$, $y(t) \in \mathbb{R}^m$ and x_t is defined by $x_t(\tau) = x(t+\tau)$ for $-h < \tau < 0$, $h > 0$. Correspondingly B_0 is a real $n \times l$ -matrix and L and C are bounded linear functionals on $C = C[-h, 0; \mathbb{R}^n]$ with values in \mathbb{R}^n and \mathbb{R}^m , respectively. These can be written in the form

$$L\phi = \int_{-h}^0 d\eta(\tau)\phi(\tau), \quad C\phi = \int_{-h}^0 d\gamma(\tau)\phi(\tau), \quad \phi \in C,$$

where $\eta(\tau)$ and $\gamma(\tau)$ are normalized functions of bounded variation, i.e. they vanish for $\tau > 0$, are constant for $\tau < -h$ and left continuous for $-h < \tau < 0$.

It is well known that equation (3.1) admits a unique solution $x(\cdot) \in L_{loc}^p[-h, \infty; \mathbb{R}^n] \cap W_{loc}^{1,p}[0, \infty; \mathbb{R}^n]$ for every input $u(\cdot) \in L_{loc}^p[0, \infty; \mathbb{R}^l]$ and every initial condition of the form

$$(3.2) \quad x(0) = \phi^0, \quad x(\tau) = \phi^1(\tau), \quad -h < \tau < 0,$$

where $\phi = (\phi^0, \phi^1) \in \mathbb{R}^n \times L^p[-h, 0; \mathbb{R}^n] = M^p$. Moreover, in these spaces the solution $x(\cdot)$ of (3.1) and (3.2) depends continuously on ϕ and $u(\cdot)$. This has motivated the definition of the state of system (3.1) at time $t > 0$ to be the pair

$$(3.3) \quad \hat{x}(t) = (x(t), x_t) \in M^p.$$

The evolution of $\hat{x}(t)$ can be described by the variation-of-constants formula

$$(3.4) \quad \hat{x}(t) = S(t)\phi + \int_0^t S(t-s)Bu(s)ds, \quad t > 0,$$

where $B \in L(\mathbb{R}^l, M^p)$ maps $u \in \mathbb{R}^l$ into the pair $Bu = (B_0u, 0)$ and $S(t) \in L(M^p)$ is the

strongly continuous semigroup generated by

$$\begin{aligned} D(A) &= \{\phi \in M^P \mid \phi^1 \in W^{1,P}, \phi^1(0) = \phi^0\}, \\ A\phi &= (L\phi^1, \dot{\phi}^1). \end{aligned}$$

Here $W^{1,P}$ denotes the Sobolev space $W^{1,P}[-h, 0, \mathbb{R}^n]$.

We will consider the evolution of the state (3.3) of system (3.1) in the dense subspace $\{(\phi(0), \phi) \mid \phi \in W^{1,P}\} \subset M^P$ which we shall identify with $W^{1,P}$. Then B becomes an 'unbounded' operator ranging in the larger space M^P . However, it follows from the uniqueness and continuous dependence result for the solutions of (3.1) and (3.2) that the state $\hat{x}(t)$ of (3.1), (3.2) defines a continuous function in $W^{1,P}$ provided that $\phi \in W^{1,P}$ and $u(\cdot) \in L_{loc}^P[0, \infty, \mathbb{R}^k]$. Hence, the operators A and B satisfy hypothesis (H1) with $Z = M^P$ and $X = W^{1,P}$. This implies that the state $\hat{x}(t) \in W^{1,P}$ of (3.1), (3.2) with $\phi \in W^{1,P}$ satisfies the Cauchy problem

$$\begin{aligned} (3.5) \quad d/dt \hat{x}(t) &= A\hat{x}(t) + Bu(t), \quad \hat{x}(0) = \phi \in W^{1,P}, \\ y(t) &= C\hat{x}(t), \end{aligned}$$

in the sense of Remark 2.2(ii). Of course, the output operator $C : W^{1,P} \rightarrow \mathbb{R}^m$ is given by

$$C\phi = \int_{-h}^0 d\gamma(\tau) \phi^1(\tau), \quad \phi \in W^{1,P}.$$

On the state space $W^{1,P}$ this operator is bounded.

REMARKS 3.1

(i) If the equation

$$(3.6) \quad \eta(\tau) = \eta(-h) + A_1, \quad -h < \tau \leq \epsilon - h,$$

holds for some $\varepsilon > 0$, then the generalized eigenfunctions of A are complete in M^P and in $W^{1,P}$ if and only if

$$(3.7) \quad \det A_1 \neq 0$$

(see MANITIUS [9], SALAMON [14, chapter 3]).

(ii) It is well known that the operator A satisfies (H3).

(iii) The exponential growth of the semigroup $S(t)$ on the complementary subspace X^Λ corresponding to $\Lambda = \{\lambda \in \sigma(A) \mid \operatorname{Re} \lambda > 0\}$ is determined by $\sup\{\operatorname{Re} \lambda \mid \lambda \in \sigma(A), \operatorname{Re} \lambda < 0\} < 0$.

(iv) Let (2.15) denote the reduced finite dimensional system obtained by spectral projection of the solutions of (3.5) on the generalized eigenspace X_Λ . Then (2.15) is controllable iff

$$(3.8) \quad \operatorname{rank}[\lambda I - L(e^{\lambda \cdot}), B_0] = n \quad \forall \lambda \in \Lambda$$

(PANDOLFI [10]) and observable iff

$$(3.9) \quad \operatorname{rank} \begin{bmatrix} \lambda I - L(e^{\lambda \cdot}) \\ C(e^{\lambda \cdot}) \end{bmatrix} = n \quad \forall \lambda \in \Lambda$$

(BEAT-KOIVO [1], SALAMON [13], [14]).

Combining these facts with Proposition 2.6 and Theorem 2.5, we obtain the following existence result for a finite dimensional compensator for system (3.1).

THEOREM 3.2

If (3.6-9) are satisfied, then there exists a finite dimensional compensator of the form (2.9) such that the closed loop system (3.1), (2.9) is exponentially stable.

3.2 RETARDED SYSTEMS WITH INPUT DELAYS

In this section we consider the RFDE

$$(3.10) \quad \begin{aligned} \dot{x}(t) &= Lx_t + Bu_t, \\ y(t) &= C_0 x(t), \end{aligned}$$

with general delays in the state and input and no delays in the output variable. This time C_0 is a real $m \times n$ - matrix and B a bounded linear functional on $C[-h, 0; \mathbb{R}^l]$ with values in \mathbb{R}^n given by

$$B\xi = \int_{-h}^0 d\beta(\tau)\xi(\tau), \quad \xi \in C[-h, 0; \mathbb{R}^l],$$

where $\beta(\tau)$ is an $n \times l$ - matrix valued, normalized function of bounded variation. Of course, we can immediately get an existence result for a finite dimensional compensator for system (3.10) by dualizing Theorem 3.2. However, for reasons to become clear later, we make use of a direct approach for system (3.10), following the ideas of VINTER and KWONG [18] (see also DELFOUR [6], SALAMON [14]).

First note that (3.10) admits a unique solution $x(\cdot) \in L_{loc}^p[-h, \infty; \mathbb{R}^n] \cap W_{loc}^{1,p}[0, \infty; \mathbb{R}^n]$ for every input $u(\cdot) \in L_{loc}^p[0, \infty; \mathbb{R}^l]$ and every initial condition of the form

$$(3.11) \quad \begin{aligned} x(0) &= \phi^0, \quad x(\tau) = \phi^1(\tau), \\ u(\tau) &= \xi(\tau), \quad -h < \tau < 0, \end{aligned}$$

where $\phi \in M^p$ and $\xi \in L^p[-h, 0; \mathbb{R}^l]$. In order to reformulate system (3.10) as an evolution equations in a product space, we rewrite (3.10-11) as

$$(3.12) \quad \begin{aligned} \dot{x}(t) &= \int_{-t}^0 d\eta(\tau)x(t+\tau) + \int_{-t}^0 d\beta(\tau)u(t+\tau) + f^1(-t), \\ y(t) &= C_0 x(t), \quad x(0) = f^0, \end{aligned}$$

where the pair $f = (f^0, f^1) \in M^P$, given by

$$(3.13) \quad \begin{aligned} f^0 &= \phi^0, \\ f^1(\sigma) &= \int_{-h}^{\sigma} d\eta(\tau) \phi^1(\tau - \sigma) + \int_{-h}^{\sigma} d\beta(\tau) \xi(\tau - \sigma), \quad -h < \sigma < 0, \end{aligned}$$

is regarded as the initial state of system (3.12). The corresponding state at time $t > 0$ is given by

$$(3.14) \quad \begin{aligned} \hat{x}(t) &= (x(t), x^t) \in M^P, \\ x^t(\sigma) &= \int_{\sigma-t}^{\sigma} d\eta(\tau) x(t + \tau - \sigma) + \int_{\sigma-t}^{\sigma} d\beta(\tau) u(t + \tau - \sigma) + f^1(\sigma - t). \end{aligned}$$

It has been shown in [6], [14], [18] that the evolution of this state can be described by the variation-of-constants formula

$$(3.15) \quad \hat{x}(t) = S^{T^*}(t)f + \int_0^t S^{T^*}(t-s)B^{T^*}u(s)ds, \quad t > 0.$$

Here $S^{T^*}(t) \in L(M^P)$ is the adjoint semigroup of $S^T(t) \in L(M^Q)$, $1/p + 1/q = 1$, which corresponds to the transposed equation $\dot{x}(t) = L^T x_t$ in the sense of section 3.1. Since $S^T(t)$ restricts to a semigroup on the dense subspace $W^{1,Q} \subset M^Q$, the adjoint semigroup $S^{T^*}(t)$ extends to the dual space $W^{-1,P} = (W^{1,Q})^*$ which contains M^P as a dense subspace in a natural way. The input operator $B^{T^*} \in L(R^k, W^{-1,P})$ is the adjoint operator of $B^T \in L(W^{1,Q}, R^k)$ given by

$$B^T \psi = \int_{-h}^0 d\beta(\tau) \psi^1(\tau) \in R^k, \quad \psi \in W^{1,Q} \subset M^Q.$$

Since the infinitesimal generator A^{T^*} of $S^{T^*}(t)$ and the input operator B^{T^*} satisfy the hypothesis (H1) of section 2 with $X = M^P$ and $Z = W^{-1,P}$ (see SALAMON [14]), the state $\hat{x}(t) \in M^P$ of system (3.12), given by (3.14), defines the unique solution of the abstract

Cauchy problem

$$(3.16) \quad \begin{aligned} d/dt \hat{x}(t) &= A^T \hat{x}(t) + B^T u(t), \quad \hat{x}(0) = f \in M^P \\ y(t) &= Cx(t), \end{aligned}$$

in the sense of Remark 2.2(ii). Of course, the output operator $C : M^P \rightarrow R^m$ is now given by

$$Cf = c_0 f^0 \in R^m, \quad f \in M^P.$$

In order to make the results of this section more precise, we briefly outline the construction of the reduced system (2.15). For this purpose let $X_\Lambda \subset W^{1,P}$ and $X_\Lambda^T \subset W^{1,Q}$ denote the generalized eigenspaces of A and A^T , respectively, corresponding to $\Lambda = \{\lambda \in \sigma(A) \mid \operatorname{Re} \lambda > 0\}$. Since Λ is a symmetric set, we can choose real bases $\{\phi_1, \dots, \phi_{N_\Lambda}\}$ of X_Λ and $\{\psi_1, \dots, \psi_{N_\Lambda}\}$ of X_Λ^T such that the matrices

$$\begin{aligned} \Phi &= [\phi_1 \dots \phi_{N_\Lambda}] \in W^{1,P}[-h, 0; R^{n \times N_\Lambda}] \\ \Psi &= [\psi_1 \dots \psi_{N_\Lambda}] \in W^{1,Q}[-h, 0; R^{N_\Lambda \times n}] \end{aligned}$$

satisfy

$$\Psi^T(0)\Phi(0) + \int_{-h}^0 \int_{\tau}^0 \Psi^T(\sigma) d\eta(\tau) \Phi(\tau - \sigma) d\sigma = I \in R^{N_\Lambda \times N_\Lambda}.$$

Then $i_\Lambda : R^{N_\Lambda} \rightarrow M^P$ and $\pi_\Lambda : M^P \rightarrow R^{N_\Lambda}$ may be defined by

$$[i_\Lambda x_\Lambda]^0 = \Phi(0)x_\Lambda, \quad [i_\Lambda x_\Lambda]^1(\sigma) = \int_{-h}^{\sigma} d\eta(\tau) \Phi(\tau - \sigma)x_\Lambda, \quad -h < \sigma < 0,$$

$$w_A f = \Psi^T(0) f^0 + \int_{-h}^0 \Psi^T(\sigma) f^1(\sigma) d\sigma$$

for $x_A \in \mathbb{R}^{N_A}$ and $f \in M^P$, and the matrices $A_A \in \mathbb{R}^{N_A \times N_A}$, $B_A \in \mathbb{R}^{N_A \times l}$, $C_A \in \mathbb{R}^{m \times N_A}$ are given by

$$A(\phi(0)\phi) = (\phi(0), \phi) A_A, \quad B_A = \int_{-h}^0 \Psi^T(\tau) d\beta(\tau), \quad C_A = C_0 \phi(0)$$

(see SALAMON [14, section 2.4]).

REMARKS 3.3

(i) If (3.6) is satisfied for some $\varepsilon > 0$, then the eigenfunctions of A^{T^*} are complete in M^P and in $W^{-1,P}$ if and only if (3.7) holds (see MANITIUS [9], SALAMON [14, chapter 3]).

(ii) If A_A, B_A, C_A are defined as above, then system (2.15) is controllable iff

$$(3.17) \quad \text{rank}[\lambda I - L(e^{\lambda^*}), B(e^{\lambda^*})] = n \quad \forall \lambda \in \Lambda$$

and observable iff

$$(3.18) \quad \text{rank} \begin{bmatrix} \lambda I - L(e^{\lambda^*}) \\ C_0 \end{bmatrix} = n \quad \forall \lambda \in \Lambda$$

(see SALAMON [14]).

Theorem 3.4

If (3.6-7) and (3.17-18) are satisfied, then there exists a finite dimensional compensator of the form (2.9), such that the closed loop system (3.10), (2.9) is exponentially stable.

Remark 3.1(i) and Remark 3.3(i) show that the completeness property of A and A^T can be destroyed by arbitrarily small perturbations in the delays (compare MANITIUS [9]). However such perturbations would not affect the stability of the closed loop system (3.1), (2.9) respectively (3.10), (2.9). This indicates that the completeness assumption is somewhat artificial for the purpose of stabilization by a finite dimensional compensator. In the next section we will show that the completeness condition can in fact be weakened in the case of systems with state delays only.

3.3 A SPECIAL CASE

In this section we consider the special case of the RFDE

$$\begin{aligned} \dot{x}(t) &= A_0 x(t) + A_1 x(t-h) + B_0 u(t), \\ y(t) &= C_0 x(t), \end{aligned} \quad (3.19)$$

with a single point delay in the state variables and no delays in control and observation. Following the ideas presented in the previous section we define the state of system (3.19) to be the pair

$$\begin{aligned} \hat{x}(t) &= (x(t), x^t) \in M^P, \\ x^t(\sigma) &= A_1 x(t-h-\sigma), \quad -h \leq \sigma \leq 0. \end{aligned} \quad (3.20)$$

This time the range of the input operator $B^{T^*} = B$ is contained in M^P , since $B^T \psi = B_0^T \psi^1(0) = B_0^T \psi^0$ for $\psi \in W^{1,q} \subset M^q$. Therefore $\hat{x}(t)$ satisfies the Cauchy

problem

$$(3.21) \quad \begin{aligned} \frac{d}{dt} \hat{x}(t) &= A^T \hat{x}(t) + Bu(t), \\ y(t) &= C\hat{x}(t). \end{aligned}$$

We will regard this as an equation in the closed subspace

$$X = \{f \in M^P | f^1(\tau) \in \text{range } A_1, -h \leq \tau \leq 0\}$$

of M^P . Of course, this means that A^{T*} has to be restricted to the domain

$$\mathcal{D}_X(A^{T*}) = \mathcal{D}_{M^P}(A^{T*}) \cap X.$$

REMARKS 3.5

(i) It has been shown by MANITIUS [9] that the eigenvectors of A^{T*} are complete in X if and only if

$$(3.22) \quad \text{rank} \begin{bmatrix} A_0 - \lambda I & A_1 \\ A_1 & 0 \end{bmatrix} = n + \text{rank } A_1$$

for some $\lambda \in \mathbb{C}$. This condition is obviously weaker than (3.7).

(ii) Clearly, the reduced finite dimensional system (2.15) remains the same when the Cauchy problem (3.21) is restricted to the closed subspace $X \subset M^P$. Therefore system (2.15) is controllable and observable if and only if

$$(3.23) \quad \begin{aligned} &\text{rank}[\lambda I - A_0 - e^{-\lambda h} A_1 B_0] \\ &= \text{rank} \begin{bmatrix} \lambda I - A_0 - e^{-\lambda h} A_1 \\ C_0 \end{bmatrix} = n \quad \forall \lambda \in \Lambda \end{aligned}$$

where $\Lambda = \{\lambda \in \mathbb{C} \mid \det(\lambda I - A_0 - e^{-\lambda h} A_1) = 0, \operatorname{Re} \lambda > 0\}$

(iii) It is easy to see that the stability of the abstract closed loop system (3.21), (2.9) in the state space $X \times \mathbb{R}^N$ implies the stability of the closed loop delay equation (3.19), (2.9).

Again combining these facts with the results of section 2, we obtain the following existence result for a finite dimensional compensator. For system (3.19) this is a stronger result than one would obtain by applying the theory of [16].

THEOREM 3.6

If (3.22) and (3.23) are satisfied then there exists a finite dimensional compensator of the form (2.9) such that the closed loop system (3.19), (3.20) is exponentially stable.

REMARK 3.7

This result suggests that it should be possible to weaken the completeness assumption for the general RFDE which would be an important improvement. Another extension would be an existence result for RFDEs with delays in simultaneously the control and the observation. However, it is not obvious how this can be achieved with the present approach, the main difficulty being the completeness property.

REMARK 3.8

Although the main results of this section, Theorems 3.2, 3.4 and 3.6 are stated as existence results, we emphasize that the stabilizing compensator can in fact be constructed using exactly the same procedure as it is explained in detail in [16] for RFDEs without delays in the external variables. The construction, as outlined in the proof of Proposition 2.6, involves calculating finitely many eigenvalues and eigenvectors of A and hence the projected system $A_\Lambda, B_\Lambda, C_\Lambda$ as it is described in section 3.2. Then the matrices F_Λ and G_Λ can be calculated by standard finite dimensional procedures.

The most difficult part of the design lies in finding eigenvectors of $A + BF$ to generate the subspace W . The approximation of $G = \int_0^\infty e^{-At} B B^* e^{-At} dt$ by an operator \hat{G} with range in W then reduces to a finite dimensional linear optimization procedure. This procedure has to be repeated - while increasing W - until \hat{G} is close enough to G . The numerical example for a retarded system examined in [16] gives insight into the details of the design procedure.

4. BOUNDARY CONTROL SYSTEMS

The purpose of this section is to show how abstract boundary control systems in Hilbert spaces fit into the framework of section 2. When these results are applied to obtain finite dimensional compensators for particular classes of partial differential equations (PDE), there is a considerable overlap with results of CURTAIN in [2], [3], [4]. The relation between both approaches will be discussed in detail at the end of this section.

Let W, X, U, Y be Hilbert spaces and suppose that

$$W \subset X$$

with a continuous, dense injection. Furthermore, let $A \in L(W, X)$, $\Gamma \in L(W, U)$, $C \in L(X, Y)$ be given. Then we consider the boundary control system

$$\begin{aligned} (4.1) \quad & d/dt \, x(t) = Ax(t), \quad x(0) = x_0 \in W, \\ & \Gamma x(t) = u(t), \quad t > 0, \end{aligned}$$

with the output

$$(4.2) \quad y(t) = Cx(t), \quad t > 0.$$

DEFINITION 4.1 (strong solution, wellposedness)

(i) Let $u(\cdot) \in C[0, T; U]$ and $x_0 \in W$ satisfy $\Gamma x_0 = u(0)$. Then a function
 $x(\cdot) \in C[0, T; W]$ is said to be a (strong) solution of (4.1) if $x(\cdot) \in C^1[0, T; X]$ and if
(4.1) is satisfied for every $t \in [0, T]$.

(ii) The boundary control system (4.1) is said to be well posed if the subspace
 $\{x \in W | \Gamma x = 0\}$ is dense in X , and if for all $x_0 \in W$ and $u(\cdot) \in W^{1,2}[0, T; U]$ with
 $\Gamma x_0 = u(0)$ there exists a unique solution $x(\cdot) \in C[0, t; W] \cap C^1[0, T; X]$ of (4.1)
depending continuously on x_0 and $u(\cdot)$. This means that there exists a constant
 $K > 0$ such that the inequality

$$\sup_{0 \leq t \leq T} \|x(t)\|_W + \sup_{0 \leq t \leq T} \|\dot{x}(t)\|_X \leq K \{ \|x_0\|_W + \left[\int_0^T \|u(t)\|_U^2 dt \right]^{1/2} \}$$

holds for every solution $x(t)$ of (4.1).

REMARKS 4.2

Let system (4.1) be well posed.

(i) Taking $u(t) \equiv 0$, it follows from a classical result in semigroup theory (PHILLIPS [11]) that the operator

$$(4.3) \quad Ax = \Delta x, \quad \mathcal{D}(A) = \{x \in W | \Gamma x = 0\}$$

is the infinitesimal generator of a strongly continuous semigroup $S(t)$ on X and that, for every $x_0 \in \mathcal{D}(A)$, the function $x(t) = S(t)x_0$ is the solution of (4.1) with $u(t) \equiv 0$.

(ii) As in section 2 we introduce the dense subspace $Z^* = \mathcal{D}_{X^*}(A^*) \subset X^*$. Then

$$X \subset Z$$

with a continuous, dense injection, A extends to a bounded operator from X to Z and $S(t)$ to a strongly continuous semigroup on Z .

(iii) It follows from [14, Lemma 1.3.2(i)] that

$$\{x \in W \mid \Gamma x = 0\} = \mathcal{D}_X(A) = \{x \in X = \mathcal{D}_Z(A) \mid Ax \in X\}$$

or in other words, if $x \in X$ and $Ax \in X$, then $x \in W$ and $\Gamma x = 0$. Furthermore, the W -norm on $\mathcal{D}_X(A)$ is equivalent to the graph norm of A ([14, Remark 1.3.1(iii)]). This means that there exists a constant $K_1 > 0$ such that the inequality

$$\|x\|_W \leq K_1 [\|x\|_X + \|Ax\|_X]$$

holds for all $x \in W$ with $\Gamma x = 0$.

(iv) Γ is onto. Hence there exists a constant $K_0 > 0$ such that for every $u \in U$ there exists a $w \in W$

$$(4.4) \quad \Gamma w = u, \quad \|w\|_W \leq K_0 \|u\|_U.$$

Let us now construct the input operator $B \in \mathcal{L}(U, Z)$.

1. Given $u \in U$ we may choose $w \in W$ such that $\Gamma w = u$ since Γ is onto (Remark 4.2(iv)). For this $w \in W$ we define $Bu := \Delta w - Aw \in Z$. This expression is well defined since $\Gamma w = 0$ if and only if $Aw = \Delta w$ (Remark 4.2(iii)). Hence the map $B : U \rightarrow Z$ satisfies, by definition, the equation

$$(4.5) \quad B\Gamma x = \Delta x - Ax, \quad x \in W.$$

2. It is easy to see that B is a linear map.

3. Let $u \in U$ be given and choose $w \in W$ such that (4.4) holds. Then

$$\begin{aligned} \|Bu\|_Z &\leq \|A - A\|_{L(W,Z)} \|w\|_W \\ &\leq K_0 \|A - A\|_{L(W,Z)} \|u\|_U \end{aligned}$$

and therefore $B : U \rightarrow Z$ is bounded.

LEMMA 4.3

Let the operators A and B be defined by (4.3) and (4.5), respectively.

Furthermore, let $x \in X$ and $u \in U$ satisfy $Ax + Bu \in X$. Then

$$x \in W, \quad \Gamma x = u, \quad \Delta x = Ax + Bu.$$

Furthermore there exists a constant $K > 0$ such that

$$\|x\|_W \leq K[\|x\|_X + \|u\|_U + \|Ax + Bu\|_X]$$

for all $x \in X, u \in U$ with $Ax + Bu \in X$.

PROOF Let $x \in X$ and $u \in U$ satisfy $Ax + Bu \in X$ and choose $w \in W$ such that (4.4) holds. Then

$$A(x-w) = Ax + Bu - (A+B\Gamma)w = Ax + Bu - \Delta w \in X.$$

By Remark 4.2(iii), this implies that $x \in W$ and

$$\begin{aligned} \|x\|_W &\leq \|w\|_W + \|x - w\|_W \\ &\leq \|w\|_W + K_1[\|x - w\|_X + \|A(x - w)\|_X] \end{aligned}$$

$$\begin{aligned}
& \leq [1 + K_1 \|Id\|_{L(W,X)} + K_1 \|A\|_{L(W,X)}] \|w\|_W \\
& \quad + K_1 \|x\|_X + K_1 \|Ax + Bu\|_X \\
& \leq K [\|u\|_U + \|x\|_X + \|Ax + Bu\|_X] .
\end{aligned}$$

Finally, we obtain again from Remark 4.2(iii) that $\Gamma x = \Gamma w = u$ and from (4.5) that

$$\Delta x = Ax + B\Gamma x = Ax + Bu . \square$$

The above operators A and B allow us to reformulate the boundary control system (4.1) as a Cauchy problem of the type (2.1). More precisely, we introduce the following concept of a weak solution for (4.1).

DEFINITION 4.4 (weak solution)

Let the operators $A \in L(X,Z)$ and $B \in L(U,Z)$ be defined as above. Moreover, let $x_0 \in X$ and $u(\cdot) \in L^2[0,T;U]$ be given. Then $x(\cdot) \in C[0,T;X] \cap W^{1,2}[0,T;Z]$ is said to be a weak solution of (4.1) if

$$\begin{aligned}
& d/dt \, x(t) = Ax(t) + Bu(t) , \quad 0 \leq t \leq T , \\
(4.6) \quad & x(0) = x_0
\end{aligned}$$

is satisfied in Z (almost everywhere).

It follows from the definition of the operator B (Remark 4.2(iv)) that every strong solution $x(\cdot) \in C[0,T;W] \cap C^1[0,T;X]$ of (4.1) is a weak solution in the sense of Definition 4.4. Moreover we have the following result.

PROPOSITION 4.5

Suppose that the operator A defined by (4.3) is the infinitesimal generator of a strongly continuous semigroup S(t) on X and that $\Gamma \in L(W, U)$ is onto. Furthermore let B $\in L(U, Z)$ be defined by (4.5). Then the following statements are equivalent.

- (i) System (4.1) is well posed.
- (ii) The operators A and B satisfy hypothesis (H1) of section 2 with p = 2.
- (iii) For every $x_0 \in X$ and every $u(\cdot) \in L^2[0, T; U]$ there exists a unique weak solution $x(\cdot) \in C[0, T; X] \cap W^{1,2}[0, T; Z]$ of (4.1) depending continuously on x_0 and $u(\cdot)$.

Moreover, the weak (and in particular the strong) solutions of (4.1) are given by

$$(4.7) \quad x(t) = S(t)x_0 + \int_0^t S(t-s)Bu(s)ds \in X, \quad 0 \leq t \leq T.$$

PROOF It is a well known semigroup theoretic result that the solutions of (4.6), and therefore the weak solutions of (4.1), are given by (4.7). Furthermore, it follows from Remark 2.2(ii) that (ii) is equivalent to (iii).

In order to prove that (ii) implies (i), suppose that (H1) is satisfied and let $x(t)$ be given by (4.7) with $x_0 \in W$ and $u(\cdot) \in C^1[0, T; U]$ satisfying $\Gamma x_0 = u(0)$. Then it is a well known result from semigroup theory that $x(\cdot) \in C[0, T; X] \cap C^1[0, T; Z]$ satisfies

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ &= S(t)[Ax_0 + Bu(0)] + \int_0^t S(t-s)\dot{B}u(s)ds \\ &= S(t)\dot{A}x_0 + \int_0^t S(t-s)\dot{B}u(s)ds, \quad 0 \leq t \leq T. \end{aligned}$$

By (H1) and Remark 2.1(ii), this implies that $\dot{x}(\cdot) \in C[0, T; X]$ and

$$\sup_{0 \leq t \leq T} \|\dot{x}(t)\|_X \leq \sup_{0 \leq t \leq T} \|S(t)\|_{L(X)} \|\Delta\|_{L(W, X)} \|x_0\|_W + b_T \|\dot{u}(\cdot)\|_{L^2[0, T; U]}.$$

Applying Lemma 4.3 to the term $Ax(t) + Bu(t) = \dot{x}(t) \in X$, we obtain that

$x(\cdot) \in C[0, T; W] \cap C^1[0, T; X]$ satisfies (4.1). Since every strong solution of (4.1) is given by (4.7), $x(t)$ is in fact the unique solution. Furthermore, we obtain from Lemma 4.3 that

$$\|x(t)\|_W \leq K[\|x(t)\|_X + \|u(t)\|_U + \|\dot{x}(t)\|_X].$$

Since

$$\begin{aligned} \sup_{0 \leq t \leq T} \|x(t)\|_X &\leq \sup_{0 \leq t \leq T} \|S(t)\|_{L(X)} \|\Delta\|_{L(W, X)} \|x_0\|_W \\ &\quad + b_T \|\dot{u}(\cdot)\|_{L^2[0, T; U]} \end{aligned}$$

and

$$\sup_{0 \leq t \leq T} \|u(t)\|_U \leq \|\Gamma\|_{L(W, U)} \|x_0\|_W + \sqrt{T} \|\dot{u}(\cdot)\|_{L^2[0, T; U]}$$

for $u(\cdot) \in C^1[0, T; U]$ with $u(0) = \Gamma x_0$, this shows that system (4.1) is well posed.

Conversely, suppose that system (4.1) is wellposed in the sense of Definition 4.1, let $v(\cdot) \in C^1[0, T; U]$ and define

$$x(t) = \int_0^t S(t-s) B \int_0^s v(\tau) d\tau ds, \quad u(t) = \int_0^t v(\tau) d\tau, \quad 0 \leq t \leq T.$$

Then $x(\cdot) \in C^1[0, T; Z]$ and

$$Ax(t) + Bu(t) = \dot{x}(t) = \int_0^t S(t-s) B v(s) ds, \quad 0 \leq t \leq T.$$

Hence $x(\cdot) \in C^1[0, T; X]$ and we obtain from Lemma 4.3 that $x(\cdot) \in C[0, T; W]$, $\Gamma x(t) = u(t)$ and $\Delta x(t) = Ax(t) + Bu(t)$. Hence $x(t)$ is a strong solution of (4.1) in the sense of Definition 4.1(i) and satisfies the inequality

$$\left\| \int_0^T S(T-s)Bv(s)ds \right\|_X = \|x(T)\|_X \leq K \|v(\cdot)\|_{L^2[0, T; U]}.$$

This shows that the operators A and B satisfy the hypothesis (H1). ■

Having established hypothesis (H1) we are now in a position to apply the perturbation result of section 2 (theorem 2.2) to the boundary control system (4.1).

COROLLARY 4.6

If system (4.1) is well posed, then the following statements holds.

(i) For every $F \in L(X, U)$ the operator

$$(4.8) \quad A_F x = \Delta x, \quad \mathcal{D}(A_F) = \{x \in W \mid \Gamma x = Fx\}$$

is the infinitesimal generator of a strongly continuous semigroup $S_F(t)$ on X .

(ii) For every $x_0 \in \mathcal{D}(A_F)$ the function $x(t) = S_F(t)x_0$, $t \geq 0$, is continuous in W , continuously differentiable in X , and satisfies the closed loop boundary control equations

$$(4.9) \quad \begin{aligned} d/dt x(t) &= \Delta x(t), \quad x(0) = x_0, \\ \Gamma x(t) &= Fx(t), \quad t \geq 0, \end{aligned}$$

where the derivative has to be understood in the space X .

(iii) If U is finite dimensional, then $S_F(t)$ extends to a strongly continuous

semigroup on Z whose infinitesimal generator is given by the extended operator

$$A + BF : X \rightarrow Z .$$

PROOF By Proposition 4.5, the operators A and B defined by (4.3) and (4.5), respectively, satisfy hypothesis (H1) of section 2. Hence it follows from Theorem 2.3(i) that the operator

$$A_F x = Ax + BFx , \quad \mathcal{D}(A_F) = \{x \in X \mid Ax + BFx \in Z\}$$

generates a strongly continuous semigroup on X (note that the proof of this result in [14, Theorem 1.3.7] does not require U to be finite dimensional). Lemma 4.3 shows that this operator A_F coincides with the one defined by (4.8). This proves statement (i).

In order to prove statement (ii), let $x_0 \in \mathcal{D}(A_F)$ be given and define $u(t) = FS_F(t)x_0$, $t \geq 0$. Then $u(t)$ is continuously differentiable for $t \geq 0$ and satisfies $u(0) = Fx_0 = \Gamma x_0$. Hence (4.1) admits a unique strong solution $x(t)$, $t \geq 0$, which by definition of the operators A and B also satisfies (4.6) and is therefore given by (4.7). This implies

$$x(t) = S(t)x_0 + \int_0^t S(t-s)BFS_F(s)x_0 ds = S_F(t)x_0 ,$$

by definition of the semigroup $S_F(t)$.

Statement (iii) is an immediate consequence of Theorem 2.3(iii). ■

So far we have shown that the general theory of section 2 also covers abstract boundary control systems. In particular, we have reformulated the boundary control system

(4.1) in the semigroup theoretic framework with an unbounded input operator. A very similar approach has been developed by HO and RUSSELL in [8] under only slightly more restrictive assumptions. However, [8] does not contain any feedback results and also the above Proposition 4.5 seems to be new. Furthermore we point out that earlier results in this direction for special classes of systems can be found e.g. in CURTAIN-PRITCHARD [5]. Another general approach has been presented by FATTORINI [7]. In [7] the input operator is bounded, however, there are derivatives in the input function which do not appear in our approach.

In [2] and [3] CURTAIN has used FATTORINI'S results for the construction of finite dimensional compensators which leads to integral terms in the loop. These integral terms will disappear if we apply the approach of this section to obtain existence results for finite dimensional compensators. More precisely, we have to assume that the operators A , B and C , introduced in this section, satisfy hypothesis (H2) of section 2, or respectively, hypothesis (H3) and the assumptions of Proposition 2.6. Under these conditions it follows readily from Theorem 2.5 that there exists a finite dimensional compensator of the form (2.9) such that the closed loop system (4.1), (4.2), (2.9) is exponentially stable.

Starting from equations (4.1), (4.2), the following problems have to be solved for the construction of the compensator.

1. Find the operators A and B .
2. Determine the spectrum of the operator A and the reduced subsystem (2.15).
3. Find the stabilizing operators $F : X \rightarrow U$ and $G : Y \rightarrow X$.
4. Determine the eigenvalues and eigenvectors of A_p to approximate G .

To illustrate this procedure, we consider the heat equation with Neumann boundary conditions and boundary control which has also been treated in [3] with different methods.

EXAMPLE 4.7

Consider the parabolic PDE

$$\begin{aligned}
(4.10;1) \quad & z_t = \pi^{-2} z_{\xi\xi}, \quad 0 < \xi < 1, \quad t > 0, \\
(4.10;2) \quad & z_{\xi}(0,t) = u(t), \quad z_{\xi}(1,t) = 0, \quad t > 0, \\
(4.10;3) \quad & z(\xi,0) = z_0(\xi), \quad 0 < \xi < 1, \\
(4.10;4) \quad & y(t) = \int_0^1 c(\xi) z(\xi,t) d\xi, \quad t > 0.
\end{aligned}$$

This system can be written in the abstract form (4.1) with

$$X = L^2[0,1], \quad W = \{\phi \in H^2[0,1] \mid \dot{\phi}(1) = 0\}, \quad U = \mathbb{R},$$

$$\Delta\phi = \pi^{-2} \ddot{\phi}, \quad \Gamma\phi = \dot{\phi}(0)$$

$$Z^* = \mathcal{D}(A^*) = \mathcal{D}(A) = \{\psi \in H^2[0,1] \mid \dot{\psi}(0) = 0 = \dot{\psi}(1)\}.$$

The operator A satisfies (H3) and has a complete set of eigenvectors

$$\phi_0(\xi) \equiv 1, \quad \phi_n(\xi) = \sqrt{2} \cos n\pi\xi, \quad \text{corresponding to the eigenvalues}$$

$\lambda_0 = 0$, $\lambda_n = -n^2$, $n \in \mathbb{N}$. In order to determine the operator $B: \mathbb{R} \rightarrow Z$, let us choose any $\phi \in W$ such that $\Gamma\phi = 1$, e.g. $\phi(\xi) = -(\xi-1)^2/2$. Then, for every $\psi \in Z^*$, the following equation holds

$$B^*\psi = \langle B^*\psi, \Gamma\phi \rangle = \langle \psi, B\Gamma\phi \rangle = \langle \psi, \Delta\phi - A\phi \rangle$$

$$= \langle \psi, \Delta\phi \rangle - \langle A^*\psi, \phi \rangle$$

$$= \frac{1}{\pi^2} \int_0^1 \psi(\xi) \ddot{\phi}(\xi) d\xi - \frac{1}{\pi^2} \int_0^1 \ddot{\psi}(\xi) \phi(\xi) d\xi$$

$$= \frac{1}{\pi^2} \int_0^1 [\psi(\xi) \ddot{\phi}(\xi) + \dot{\psi}(\xi) \dot{\phi}(\xi)] d\xi$$

$$= \frac{1}{\pi^2} [\psi(1)\dot{\phi}(1) - \psi(0)\dot{\phi}(0)]$$

$$= -\frac{1}{\pi^2} \psi(0) .$$

It has been shown in PRITCHARD-SALAMON [12] that these operators A and B satisfy hypothesis (H1) and therefore system (4.10) is wellposed in $X = L^2[0,1]$ in the sense of Definition 4.1 (see Proposition 4.5). The spectral projection of $L^2[0,1]$ onto the eigenspace $X_\Lambda = \{a\phi_0 | a \in \mathbb{R}\}$ of Λ corresponding to the unstable part $\Lambda = \{0\}$ of the spectrum is given by

$$P_\Lambda \phi(\xi) = \int_0^1 \phi(\tau) d\tau , \quad 0 < \xi < 1 .$$

With the choice of $\{\phi_0\}$ as a basis of X_Λ , this operator splits into $P_\Lambda = {}^1_\Lambda \pi_\Lambda$, where $\pi_\Lambda : L^2[0,1] \rightarrow \mathbb{R}$ and ${}^1_\Lambda : \mathbb{R} \rightarrow L^2[0,1]$ are given by

$$\pi_\Lambda \phi = \int_0^1 \phi(\tau) d\tau , \quad {}^1_\Lambda x_\Lambda(\xi) = x_\Lambda , \quad 0 < \xi < 1 .$$

Then the reduced finite dimensional system (2.15) is described by the "matrices"

$$A_\Lambda = 0 , \quad B_\Lambda = -\pi^{-2} , \quad C_\Lambda = \int_0^1 c(\xi) d\xi .$$

This system is controllable and observable if and only if

$$(4.11) \quad C_\Lambda = \int_0^1 c(\xi) d\xi \neq 0 .$$

Stabilizing matrices are given e.g. by

$$F_\Lambda = \pi^2/4 , \quad G_\Lambda = -C_\Lambda^{-1}$$

so that $A_\Lambda + B_\Lambda F_\Lambda = -1/4$, $A_\Lambda + G_\Lambda C_\Lambda = -1$. Then the operator A_F with

$F = F_A \pi_A : L^2[0,1] \rightarrow R$ given by

$$\mathcal{D}(A_F) = \{ \phi \in H^2[0,1] \mid \dot{\phi}(1) = 0, \dot{\phi}(0) = \frac{\pi^2}{4} \int_0^1 \phi(\xi) d\xi \},$$

$$A_F \phi = \frac{1}{\pi^2} \ddot{\phi}.$$

The eigenvectors and eigenvalues of A_F coincide with those of A except for $\lambda_0 = 0$ which is now replaced by $\lambda_F = -1/4$. The corresponding normalized eigenfunction is

$$\phi_F(\xi) = \sqrt{2} \sin \frac{\pi}{2} \xi.$$

We will choose $W = \text{span}\{\phi_F\}$ and the maps

$$(i_F w)(\xi) = \phi_F(\xi) w, \quad 0 < \xi < 1, \quad w \in R,$$

$$(\pi_F \phi)(\xi) = \int_0^1 \phi_F(\xi) \phi(\xi) d\xi, \quad \phi \in L^2[0,1],$$

So that $i_F \pi_F : L^2[0,1] \rightarrow W$ is the orthogonal projection onto W and $\pi_F i_F = 1$.

Let us now consider the case that $c(\xi) = \xi$ for $0 < \xi < 1$. Then $C_A = 1/2$ and we choose $G_A = -\pi g / 2\sqrt{2}$, $g > 0$. With this choice the operator $G : R \rightarrow L^2[0,1]$ is given by

$$[Gy](\xi) = [i_A G_A y](\xi) = -\frac{\pi g}{2\sqrt{2}} y, \quad 0 < \xi < 1.$$

We replace this operator by

$$[\hat{G}y](\xi) = [i_F \pi_F G y](\xi) = -g y \sqrt{2} \sin \frac{\pi}{2} \xi, \quad 0 < \xi < 1,$$

whose range is in W . Since the perturbed operator $A + \hat{G}C$ generates an analytic

semigroup it satisfies the "spectrum determined growth" assumption. Furthermore, its spectrum is given by

$$\sigma(A + \hat{G}C) = \{-\omega^2 | g[1 - \cos \omega \pi] = \omega^3 [8K + \pi^2/2\sqrt{2} - \sqrt{2}\pi^2 \omega^2] \sin \omega \pi, \omega \neq 0\}$$

if $g > 0$. In the case $g < 0$ there is an additional positive eigenvalue $\lambda_0 = \omega^2 > 0$ where

$$-g \frac{e^{\omega \pi} + e^{-\omega \pi} - 2}{e^{\omega \pi} - e^{-\omega \pi}} = \omega^3 [8K + \pi^2/2\sqrt{2} + \sqrt{2}\pi^2 \omega^2].$$

We conclude that $A + \hat{G}C$ generates an exponentially stable semigroup if and only if $g > 0$. Hence the operators F and \hat{G} satisfy the hypothesis (H2) with the one dimensional subspace $W = \text{span}\{\phi_F\}$. In this case the compensator (2.9) is described by the "matrices"

$$M = \pi_F (A_F + \hat{G}C) \phi_F = -\frac{1}{4} - \frac{4\sqrt{2}}{\pi} g$$

$$H = \pi_F \hat{G} = -g$$

$$K = F \phi_F \phi_F^T = \frac{\pi}{\sqrt{2}}.$$

Hence the first order system

$$\begin{aligned} \dot{w} &= -\frac{1}{4} w - g \left[\frac{4\sqrt{2}}{\pi} w - y \right] \\ u &= \frac{\pi}{\sqrt{2}} w \end{aligned} \quad (4.12)$$

defines a stabilizing compensator for the parabolic PDE (4.10) with $c(\xi) \equiv \xi$ if and only if $g > 0$.

REMARK 4.8

The results of this section show that the abstract framework of section 2 is general enough to cover both FDEs and PDEs. We mention that the approach of this section can also be applied to damped hyperbolic systems. Hence this paper represents a complete generalization of the compensator design of SCHUMACHER [16] to infinite dimensional systems with unbounded control action. However, the degree of unboundedness which we can allow for the input/output operators is not as general as one would desire. For example, for the parabolic PDE (4.10) we cannot allow simultaneously Neumann boundary control and point observation. Also we cannot allow Dirichlet boundary control when the output operator is an arbitrary functional on $L^2[0,1]$. A general theory which covers these cases would require the consideration of unbounded output operators as well. The development of such an approach seems to involve some further difficulties and would be an interesting problem for future research.

REMARK 4.9

Using the abstract approach outlined in section 2, it is possible to directly extend the results of SCHUMACHER [15], [17] on tracking and regulation in infinite dimensions to unbounded control action. A different approach is to use the extended system formulation discussed in [2], which results in integral control action and this can be found in CURTAIN [4].

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LEND

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